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Comparison of ionospheric electrical conductances inferred from coincident radar and spacecraft measurements and photoionization models

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Abstract—Height-integrated electrical conductivities (conductances) inferred from coincident Sondrestrom incoherent scatter radar and DMSP-F7 observations in the high-latitude ionosphere during solar minimum are compared with results from photoionization models. We use radar and spacecraft measurements in combination with atmospheric and ionospheric models to distinguish between the contributions of the two main sources of ionization of the thermosphere, namely, solar UV/EUV radiation and auroral electron precipitation. The model of ROBINSON *et al.* (1987, *J. geophys. Res.* **89**, 3951) of Pedersen and Hall conductances resulting from electron precipitation appears to be in accordance with radar measurements. Published models of the conductances resulting from photoionization that use the solar zenith angle and the solar 10.7-cm radio flux as scaling parameters are, however, in discrepancy with radar observations. At solar zenith angles of less than 90, the solar radiation components of the Pedersen and Hall conductances are systematically overestimated by most of these models. Geophysical conditions that have some bearing on the state of the high-latitude thermosphere (e.g. geomagnetic and substorm activity and a seasonal variation of the neutral gas distribution) seem to influence the conductivity distribution but are to our knowledge not yet sufficiently well modelled.

1. INTRODUCTION

Ionospheric electrical conductivities are important parameters in ionospheric electrodynamics and magnetosphere–ionosphere coupling. Under many circumstances (e.g. when dealing with field-aligned current closure by Pedersen currents or Ohmic energy dissipation or ground magnetic field signatures of ionospheric currents) the knowledge of conductances (height-integrated conductivities) is sufficient and simplifies calculations considerably.

In this paper we concentrate on the high-latitude ionosphere where solar UV and EUV radiation and auroral electron precipitation are the two main energy sources that ionize the thermospheric gas. The ionization and recombination rates (and thus the electrical conductivities) depend on the spectral distribution of solar radiation, the path of the sun beams through the atmosphere, that is, the solar zenith angle, on the scale height and composition of the neutral atmosphere and possibly on the geomagnetic field. Recent papers which discuss the different parameters that influence the daytime conductances include those published by BREKKE and HALL (1988), DE LA BEAUJARDIÈRE *et al.* (1991) and SENIOR (1991).

We use Sondrestrom incoherent scatter radar measurements of the ionospheric plasma density dis-tribution to obtain estimates of the Pedersen and Hall conductances. Coincident electron flux measurements from low-altitude spacecraft make it possible to distinguish between the contributions of electron precipitation and photoionization to the electrical conductances. We have examined ten cases of coincident Sondrestrom and DMSP-F7 (Defense Meteorological Satellite Program) measurements made during the years 1984–1986 (solar minimum period). Conductance estimates from radar measurements of the electron density distribution in the dark ionosphere were in fair agreement with those obtained from spacecraft measurements of electron precipitation. This demonstrates the validity of the precipitation model suggested by ROBINSON *et al.* (1987) that we have chosen. The contribution of solar UV and EUV radiation, calculated with various photoionization models (MEHTA, 1978; SENIOR, 1980, 1991; VICKREY *et al.*, 1981; DE LA BEAUJARDIÈRE *et al.*, 1982; ROBINSON and VONDRAK, 1984; SCHLEGEL, 1988; BREKKE and HALL, 1988; RASMUSSEN *et al.*, 1988), appears to be in systematic discrepancy with radar measurements. Our observations suggest that most of these models overestimate the electrical conductances in the sunlit ionosphere.

In this paper we describe the method that we used for a quantitative comparison of radar observations

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with models, present results and discuss possible error sources to reconcile the discrepancies.

2. INSTRUMENTS AND DATA

The Sondrestrom incoherent scatter radar is located on the west coast of Greenland at 67 geodetic and 74 invariant latitude ($L \approx 13$). It operates at 1290 MHz and measures along its line-of-sight several ionospheric parameters including plasma density and temperatures. Estimates of Debye length and electron-to-ion temperature ratio are used to obtain a corrected plasma density distribution, which is used in this study. Up to 120 km altitude, the electron-to-ion temperature ratio is assumed to be one, above 120 km the temperature ratios are inferred from the backscatter spectrum (at receiver gates spaced by 55 km). A continuous temperature profile is obtained by interpolation and corrected densities are calculated iteratively, starting from the raw densities. During our experiments, the radar scanned the ionosphere in a plane perpendicular to the local shell of constant invariant latitude. Thus, each scan provides a map of the electron density distribution in an altitude vs invariant latitude plane. During a typical scan, an integration time of 20 s corresponds to a spatial average over some 20 km (0.2 invariant latitude) at 120-km altitude overhead the radar.

The DMSP-F7 spacecraft moves on a 99 inclination, 830-km altitude, circular orbit that is Sun-synchronous in the 1030–2230 local time plane. When passing through the Sondrestrom radar field-of-view, its trajectory crosses the contours of constant L at an almost right angle, that is, parallel to the radar elevation scans. The on-board electron spectrometer (RICH et al., 1985) measures one full spectrum per second over the energy range 30 eV–30 keV. The spectrometer is always directed upward and therefore does not provide pitch angle discrimination.

We discuss cases of coincident radar and spacecraft measurements that we had selected for a recent study on Joule heating rates (WATERMANN and DE LA BEAU-JARDIÈRE, 1990). During these events the satellite trajectory, mapped to 120 km altitude, was relatively close to the radar scan plane (up to about 300 km horizontal distance). We assume, as a first approximation, a two-dimensional ionosphere, with plasma parameters constant along the L shells. Close examination of electron precipitation pattern and thermal ionospheric plasma density suggests in some cases a small misalignment between contours of constant invariant latitude and poleward boundaries of the diffuse and discrete aurorae. In such cases, we have

Table 1. DMSP-F7 passes selected for comparison with radar observations

Date	UT	EL	χ	S_a	Kp
30 May 1984	1203	83	54.2	120	2 −
28 June 1984	1225	79	51.1	100	4
13 July 1984	1227	78	53.8	93	7o
08 October 1984	1151	75	82.3	75	4 −
15 January 1985	1216	85	95.2	72	2o
16 January 1985	1156	79	98.2	75	2 +
28 June 1985	1238	68	51.2	71	3 +
16 July 1985	1135	72	58.4	72	1 −
25 September 1986	1224	69	73.8	69	3 −
26 September 1986	0208	63	113.5	68	3 −

realigned the data according to the boundaries to optimize the conditions for comparison, but still have assumed no significant variation of the ionospheric parameters between radar scan plane and spacecraft trajectory.

We had no radar operation specifically scheduled for coincidence with DMSP-F7. Most of our data were acquired during incoherent scatter World Day experiments. Table 1 lists the analyzed satellite passes with date and time (UT), highest elevation (EL) of the satellite seen from the radar, the solar zenith angle (χ) at the radar site, the intensity of the 10.7-cm flux (S_a) in units of 10^{-22} W cm^{-2} s^{-1}, normalized to 1 AU and the geomagnetic activity (Kp) Note that the first nine events are dayside passes, two of them occurred at dawn at solar zenith angles slightly exceeding 90 but in an already sunlit ionosphere. The last event is the only nightside example.

3. METHOD

The usual way to determine Pedersen and Hall conductances from plasma parameters requires the altitude dependent evaluation of the conductivity equations

$$\sigma_P = \frac{N_e e}{B} \left[\frac{v_{en}\Omega_e}{v_{en}^2 + \Omega_e^2} + \frac{v_O \Omega_O}{v_O^2 + \Omega_O^2} p_O \right.$$

$$\left. + \frac{v_{O_2}\Omega_{O_2}}{v_{O_2}^2 + \Omega_{O_2}^2} p_{O_2} + \frac{v_{NO}\Omega_{NO}}{v_{NO}^2 + \Omega_{NO}^2} p_{NO} \right] \quad (1)$$

$$\sigma_H = \frac{N_e e}{B} \left[\frac{\Omega_e^2}{v_{en}^2 + \Omega_e^2} - \frac{\Omega_O^2}{v_O^2 + \Omega_O^2} p_O \right.$$

$$\left. - \frac{\Omega_{O_2}^2}{v_{O_2}^2 + \Omega_{O_2}^2} p_{O_2} - \frac{\Omega_{NO}^2}{v_{NO}^2 + \Omega_{NO}^2} p_{NO} \right] \quad (2)$$

and a subsequent height integration. The parameters p_O, p_{O_2}, and p_{NO} denote the partial pressures of ionized

atomic and molecular oxygen and nitric oxide, respectively. The other symbols have their usual meaning. The plasma density N_e is measured by the radar, the gyrofrequencies are determined by the known geomagnetic field, only the ion collision rates (primarily with neutrals) and electron collision rates (with ions and neutrals) require model assumptions. We used the MSIS-83 neutral atmosphere model (HEDIN, 1983) and collision frequencies given by SCHUNK and NAGY (1980) and integrated the conductivities from 80 to 500 km altitude. Integration up to 500 km can be important in cases of grazing incidence sunlight because the F-region can under such conditions contribute significantly to the height-integrated conductivities (RASMUSSEN et al., 1988; DE LA BEAUJARDIÈRE et al., 1991).

Auroral electron precipitation is the only significant source of E-region ionization in the dark ionosphere. The DMSP-F7 measurements of electron energy flux and average energy were used to estimate the electrical conductances after ROBINSON et al. (1987). Application of their formula [equation (3) below] requires isotropic Maxwellian electron flux. The authors have pointed out that for energies below about 500 eV the measured electron flux is considerably higher than Maxwellian because of secondary electrons while at the same time such low energy electrons contribute very little to the conductance. Therefore we use only the 460 eV–30 keV range. In (3), $\bar{E}$ denotes the average energy in keV, Φ_E the electron energy flux in ergs cm^{-2} s^{-1}, and $\Sigma_{P,H}$ the conductances in S (Siemens)

$$\Sigma_P = \frac{40\bar{E}}{16 + \bar{E}^2}\Phi_E^{0.5} \qquad (3)$$

$$\frac{\Sigma_H}{\Sigma_P} = 0.45\bar{E}^{0.85}.$$

In Fig. 1 we compare the variation of the Pedersen (a) and Hall (b) conductances (in Siemens) over invariant latitude in the dark ionosphere. The solid line represents $\Sigma_{P,H}$ obtained from DMSP electron precipitation measurements, the dashed line $\Sigma_{P,H}$ from radar thermal plasma measurements. We note that the results from both methods match reasonably well, with good agreement in Σ_P and less good agreement in Σ_H.

The situation changes once we compare observations from the sunlit ionosphere. The method to determine $\Sigma_{P,H}$ from radar measurements of N_e and models of the neutral atmosphere and collision rates remains the same as above. However, it is no longer sufficient to consider only electron precipitation as an ionization source. We have to rely on a photo-
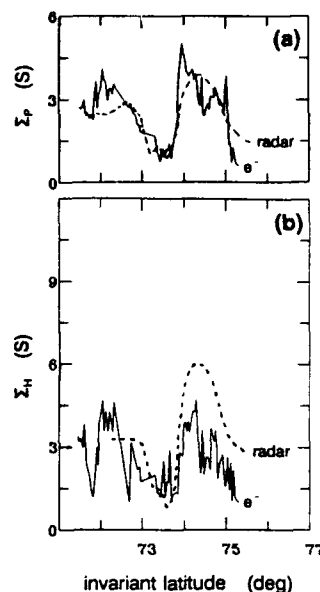

Fig. 1. (a) Σ_P and (b) Σ_H inferred from Sondrestrom radar and DMSP-F7 electron precipitation measurements made on 26 September 1986, 0208 UT, in the dark ionosphere. Only particle precipitation contributes to the E-region ionization and thus to Σ_P and Σ_H.

ionization model if we do not use direct measurements. Having estimated the conductance term owing to electron precipitation, $\Sigma_{P,H}(e^-)$ and to photoionization, $\Sigma_{P,H}(uv/euv)$, we use the following approximate combination to obtain the total conductance

$$\Sigma_{P,H}^2 = \Sigma_{P,H}^2(e^-) + \Sigma_{P,H}^2(uv/euv). \qquad (4)$$

Assuming a Chapman-α layer, such a combination would be correct at each individual altitude and a height integration of total conductivities would yield the total conductances. Because the electron precipitation and photoionization models that we use provide only height-integrated conductivities we follow the opposite approach, first height integration of the precipitation and photoionization terms individually and then combination following (4). These operations do not commute; thus, we introduce an error. If one of the terms on the right-hand side is small compared to the other, the result is not very sensitive to such an error. Therefore, we restrict our quantitative dayside comparison to those invariant latitudes where the particle precipitation was weak and therefore $\Sigma(e^-)$ small. Specifically, in all ten cases presented we found $\Sigma_P(e^-) < 1.0$ S and $\Sigma_H(e^-) < 1.3$ S.
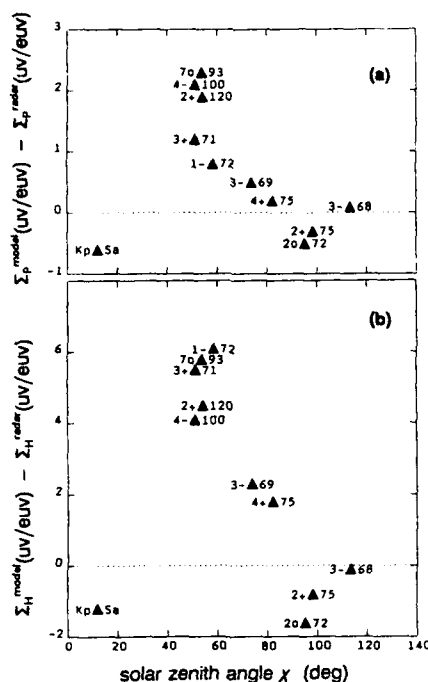
Fig. 4. Differences between measured and modelled iono-spheric conductances, (a) Σ_P and (b) Σ_H, owing to solar UV/FUV radiation. The numbers to the right of the triangles indicate the 10.7-cm flux in units of 10^{-22} W m^{-2} s^{-1}, the numbers to the left the Kp index during the time of the DMSP pass. The differences increase with decreasing solar zenith angle.

not merely a result of poor spatial or temporal coinci-dence, for the following reasons. The discrepancy emerged under almost perfect as well as imperfect coincidence between radar and satellite measure-ments. The solar radiation is globally constant and usually varies only slowly with time (except as a conse-quence of solar flare effects, when the ionization can change substantially within a few seconds). The solar zenith angle varies by not more than 1 per 110 km displacement. The intervals selected are characterized by low intensity of electron precipitation, such that the auroral precipitation component of the conductances was always below 1.3 S. We therefore suggest that the dependence of Σ_P and Σ_H on χ, or alternatively on season, has not yet been correctly modelled.

BARTH et al. (1990) demonstrated that the cor-relation between the solar 10.7-cm flux and the solar Lyman-α intensity is generally weak, in the short-term over a few solar rotations as well as in the long-term over a complete solar cycle. In particular during solar minimum, the Lyman-α intensity can drop con-siderably, while the 10.7-cm flux does not fall below a threshold of about 70 units. The Lyman-α radiation (10.2 eV) is the most intense solar UV emission. It does not provide enough energy for any of the more efficient atmospheric ionization processes

$$N_2 + 15.6\,eV \rightarrow N_2^+ + e$$

$$O_2 + 12.1\,eV \rightarrow O_2^+ + e$$

$$O + 13.6\,eV \rightarrow O^+ + e \ .$$
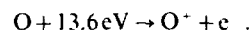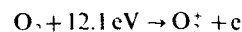
However, other terms of the Lyman series (Lyman-β and higher terms) are very efficient in O_2 ionization. Still other UV and EUV solar emissions are neither related to the 10.7-cm emission nor to the Lyman series. Altogether we expect that the ionizing com-ponents of the solar spectrum are not well correlated with S_a. It remains to be shown whether Lyman-α can serve as a more appropriate parameter.

The geomagnetic activity influences the state of the high atmosphere, for example, by heating and up-welling of the neutral air, accompanied by a change in the density ratio of atomic to molecular neutral species. Such heating can be very localized (e.g. during substorms) and may not be well represented by the global Kp index. Particularly at high latitudes the AE index of electrojet intensity may have to be incor-porated into the conductivity model. None of the models accounts for such an effect.

Some uncertainties in the application of the ROBIN-SON et al. (1987) precipitation ionization model remain, despite the fairly good agreement between their model and height-integrated conductances

is evident. The three events with larger S_a suggest that, for a constant χ, the variation of Σ_P with S_a is not properly accounted for by the model. These systematic differences may as well be interpreted as seasonal effect. Owing to the high latitude of Sondrestrom (solar zenith angles near 50 occur only in summer) season and solar zenith angle are correlated in our data. There may also exist a dependence on the geo-magnetic activity because the most disturbed interval ($Kp = 7o$) is associated with the largest discrepancy.

The comparison of measured and modelled Hall conductances [Fig. 4(b)] shows a similar trend, except that no systematic variation with geomagnetic activity (Kp dependence) is observed. The difference between the ROBINSON and VONDRAK (1984) model of Σ_H and the radar observations is much larger than in the case of the Pedersen conductance.

5. DISCUSSION

The observed discrepancies between models and Sondrestrom radar measurements of Σ_P and Σ_H are

obtained from radar measurements. The model assumes isotropic Maxwellian electron flux. Because the DMSP electron spectrometer was always pointing toward the zenith, the hypothesis of isotropic flux can be neither confirmed nor denied. It is known [e.g. from auroral electron fluxes observed on Spacelab-1, see BARROW et al. (1991)] that auroral electron precipitation is sometimes nonisotropic.

6. CONCLUSION

We have compared ionospheric plasma parameters in the auroral zone, inferred from nearly coincident Sondrestrom radar and DMSP-F7 measurements and obtained the following results.

The Pedersen and Hall conductance components associated with energetic electron precipitation are well represented by the model of ROBINSON et al. (1987). It is therefore possible to use their formulae to approximately separate the electron precipitation from the photoionization contribution to the height-integrated conductivities, in particular when the ionization due to particle precipitation is low.

The ionization of the atmosphere induced by solar UV and EUV is systematically overestimated by most available conductance models such as those presented by ROBINSON and VONDRAK (1984), RASMUSSEN et al.

(1988) and others. The discrepancy between radar measurements and model calculations increases with decreasing solar zenith angle and, at least in the case of the Pedersen conductance, with increasing solar 10.7-cm flux and possibly with increasing geomagnetic activity. Possible error sources include unsatisfactory modelling of the solar zenith angle dependence and the poor correlation between certain components of the solar UV and EUV radiation and 10.7-cm flux intensity (BARTH et al., 1990). Variations of the state of the high-latitude neutral atmosphere, owing to variations in geomagnetic activity, in particular substorm activity, and to seasonal effects, are neglected in the models. This may also contribute to the errors. But our data base is still too small to identify definite Kp-dependent and seasonal effects. Analysis of a larger number of cases is required to assess quantitatively the dependence of Pedersen and Hall conductances on various geophysical conditions including monitored variations in the state of the neutral atmosphere.

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